

Total pion–proton cross section from the new LHCf data on leading neutrons spectra

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Abstract In the light of the latest data by the LHCf collaboration of the LHC on leading neutrons spectra it is possible to obtain total pion–proton cross sections in the TeV energy region. In this work the exact extraction procedure is shown. Final results for the pion–proton cross section are collected at several different values of the colliding energy and compared with some popular theoretical predictions. The errors of the results are estimated.

1 Introduction

In previous papers we brought forward (and discussed) the idea of using the leading neutrons spectra at LHC to extract the total [1], elastic [2], and inclusive di-jet [3] cross sections of the π^+p and $\pi^+\pi^+$ scattering processes. Actually, this could allow the use of the LHC as a πp and $\pi\pi$ collider. Certainly, at LHC it would be difficult to measure exclusive channels but, instead, inclusive spectra of fast leading neutrons seem to give an excellent occasion to get pion cross sections at unimaginable energies, 1–5 TeV in the c.m.s. For further motivation and technical details we refer the reader to Refs. [1–4].

The process of leading neutron production has been studied at several experiments in photon–hadron [5–12] and hadron–hadron [13–19] colliders.

In this paper we consider process of the type $p + p \rightarrow n + X$ in the light of new data from the LHCf collaboration [20]. Recently some calculations were made in [21–24], where the authors paid attention basically to the photon–proton reaction, while for hadron collisions the situation was estimated to be not so clear (see [23,24]).

The leading neutron production is dominated by π exchange [21–24] and we have a chance to extract total π^+p cross sections.

Since the energy becomes large, we have to take into account effects of soft rescattering which can be calculated as corrections to the Born approximation. In the calculations of such absorptive effects we use Regge-eikonal approach [25], which is corrected by the use of new data from TOTEM [26].

In the first part of the paper an overview of the method is given, while in the last section this method is applied to the recent data from the LHCf collaboration [20].

The result shows that our previous proposals to use this method in CMS ZDC look rather realistic.

2 Single pion exchange and a method to extract pion–proton total cross section

Details of calculations can be found in [1,2]. Here we give an overview of basic methods. As an approximation for π exchanges we use the formulas shown graphically in Fig. 1.

In the model we have to take into account absorptive corrections depicted as S in Fig. 1. In our previous papers we used the model [27] with three pomerons for this task. In the present work we apply the Regge-eikonal model [25] with three pomerons and two odderons, since it better fits the data, including also the latest results from TOTEM [26]. Although in the region of the Single Charge Exchange (SCE) process (3) at the LHC almost all the models describe the data rather well, and possible theoretical errors are small.

We consider only absorption in the initial state (elastic absorption), since other corrections are not so important at very low values of t . Arguments in favor of this statement can be found, for example, in Ref. [21], where different types of corrections were analyzed. Although some authors [23,28,29] argued that there is an additional suppression due to interactions of “color octet states” in proton remnants with the final neutron, we have some doubts that the lifetime of final state fluctuations is large enough and interaction between colorless neutron with “color

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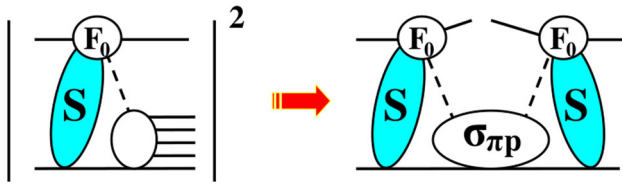


Fig. 1 Amplitude squared and the cross section of the process $p + p \rightarrow n + X$ (Single pion Exchange, $S\pi E$). S represents soft rescattering corrections

octets" is important, at least, at low momentum transfer squared.

Finally we have the expression for the single pion exchange ($S\pi E$) cross section,

$$\frac{d\sigma_{S\pi E}}{d\xi dt} = F_0(\xi, t) S(s/s_0, \xi, t) \sigma_{\pi^+ p}(\xi s; \{m_p^2, t\}), \quad (1)$$

$$F_0(\xi, t) = \frac{G_{\pi^+ pn}^2}{16\pi^2} \frac{-t}{(t - m_\pi^2)^2} e^{2bt} \xi^{1-2\alpha_\pi(t)}, \quad (2)$$

where the pion trajectory is $\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2)$. The slope $\alpha'_\pi \simeq 0.9 \text{ GeV}^{-2}$, $\xi = 1 - x_L$, where x_L is the fraction of the initial proton's longitudinal momentum carried by the neutron, and $G_{\pi^0 pp}^2/(4\pi) = G_{\pi^+ pn}^2/(8\pi) = 13.75$ [30,31]. From recent data [9,32], we expect $b \simeq 0.3 \text{ GeV}^{-2}$. We are interested in the kinematical range

$$0.01 \text{ GeV}^2 < |t| < 0.5 \text{ GeV}^2, \quad \xi_i < 0.4, \quad (3)$$

where Eqs. (1) dominate according to [33,34].

The behavior of $S t/m_\pi^2$ is shown in Fig. 2. It is clear from the figure that $|S| \sim 1$ at $|t| \sim m_\pi^2$, which is an argument for the possible almost model-independent extraction of πp cross sections by the use of (1) [2].

The present design of detectors does not allow for exact t measurements, it gives only integrated cross sections in some interval $t_{\min} < t < t_{\max}$. If we assume a weak enough t -dependence of the πp cross sections, i.e.

$$\sigma_{\pi^+ p}(s; \{m_p^2, t\}) \simeq \sigma_{\pi^+ p}(s; \{m_p^2, m_\pi^2\}), \quad (4)$$

then we could hope to extract these cross sections (though with big errors) by the following procedure:

$$\tilde{S}(\xi) = \int_{t_{\min}}^{t_{\max}} dt S(s/s_0, \xi, t) F_0(\xi, t), \quad (5)$$

$$\sigma_{\pi^+ p}(\xi s) = \frac{\frac{d\sigma_{S\pi E}}{d\xi}}{\tilde{S}(s, \xi)}, \quad \xi \simeq \frac{M_{\pi p}^2}{s}. \quad (6)$$

Function $\tilde{S}(s, \xi)$ is depicted in Fig. 3. To suppress theoretical errors of \tilde{S} we have to use total and elastic pp rates at 7 TeV, since all the models for absorptive corrections are normalized

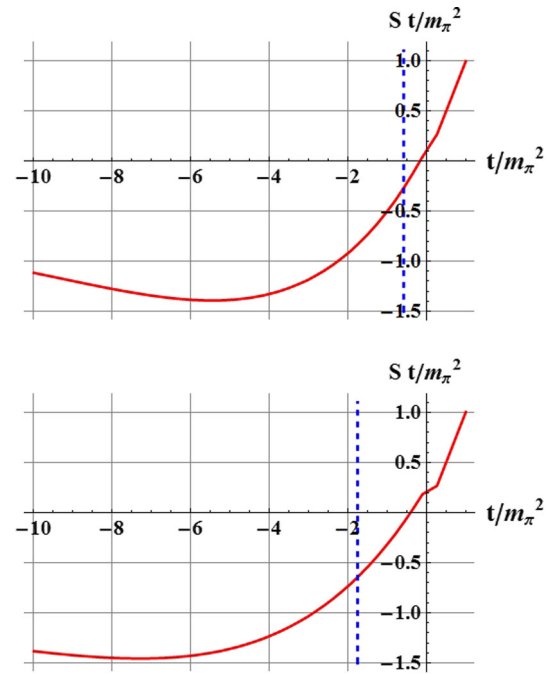


Fig. 2 Function $S(\xi, t) t/m_\pi^2$ versus t/m_π^2 at fixed $\xi = 0.107$ (upper figure) and $\xi = 0.179$ (lower figure). The boundary of the physical region $t_0 = -m_\pi^2 \xi^2 / (1 - \xi)$ is represented by vertical dashed line

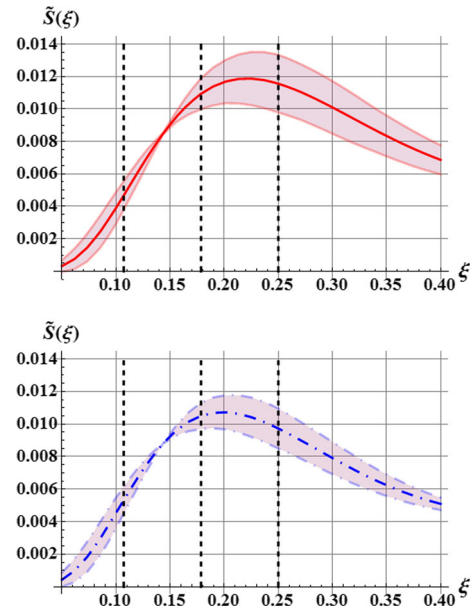


Fig. 3 Rescattering corrections multiplied by formfactors for $\sqrt{s} = 7 \text{ TeV}$ ($\tilde{S}(s, \xi)$) integrated in the whole t regions of the LHCf data [20]: $8.99 < \eta < 9.22$ (upper figure), $8.81 < \eta < 8.99$ (lower figure). Dotted vertical lines mark $\xi = 0.107, 0.179, 0.25$, which are used to extract $\sigma_{\pi p}$ cross sections

to pp cross sections. At present we can estimate these errors to be less than several percents at 7 TeV since we have precise data from TOTEM [26].

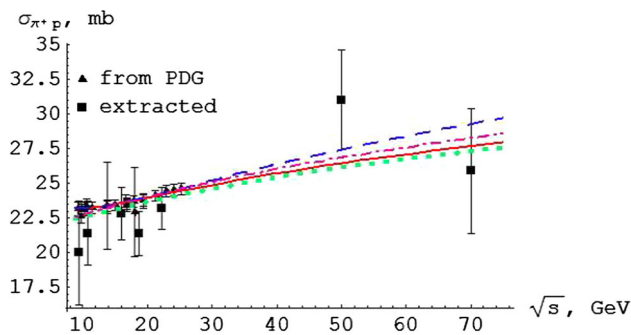


Fig. 4 Total $\pi^+ p$ cross sections versus different parametrizations: [35] (solid), [36] (dashed), [37] (dotted) and [38,39] (dash-dotted). Real data are taken from PDG (triangles) up to $\sqrt{s} = 25$ GeV and extracted values (boxes) up to $\sqrt{s} = 70$ GeV (see [1])

3 LHCf data analysis and values of pion–proton total cross sections in TeV domain

Our method developed in [1] was successfully applied to the extraction of $\pi^+ p$ total cross sections at low energies (see Fig. 4).

In this section we show results of the procedure (6) applied to the latest data on neutrons spectra by LHCf [20].

Let us first consider the data on $d\sigma_n/dE_n$ from Table A.5 of [20] in three rapidity ranges:

$$\begin{aligned} \eta &> 10.76, \\ 8.99 < \eta < 9.22, \\ 8.81 < \eta < 8.99. \end{aligned} \quad (7)$$

The first one corresponds to very low t values, where the flux factor \tilde{S} is very small, and (6) gives inadequately high values for the pion–proton cross sections. Also it is risky to use the data with huge errors at the edge of this region, where the final result may lose any significance. We use the next two regions, where $|t|$ values are of the order of m_π^2 . For these two regions we can analyze the behavior of the functions $S t/m_\pi^2$ (Fig. 2) and \tilde{S} (Fig. 3).

We also discard the data at large values of $\xi > 0.25$, since the model may not work properly for large ξ . Finally we use six data values from LHCf, which are reliable for our method (6).

Results of calculations by the method (6) are presented in the Table 1 and also shown in the Fig. 6. Corrections that correspond to backgrounds depicted in Fig. 5 are taken into account in these results.

Although errors of results are rather large, we can observe the following facts:

- These results are described well by popular models.
- Cross section continues to rise with s .
- The pion–proton cross section decreases with $|t|$ (virtuality of the pion) increasing. Experimental errors are big,

Table 1 Values of the pion–proton total cross sections extracted from the LHCf data [20] and also depicted in the Fig. 6. Corresponding average $|t|$ values (for each interval) in GeV^2 are shown in parentheses. Backgrounds from ρ and a_2 exchanges are taken into account

\sqrt{s} , TeV (ξ_{LHCf})	$\sigma_{\pi p}^{\text{tot}}$, mb ($ t $, GeV^2)	
	$8.99 < \eta < 9.22$	$8.81 < \eta < 8.99$
2.291 ± 0.382 (0.107 ± 0.035)	76.1 ± 52.3 (0.0192 ± 0.0018)	36.9 ± 26.3 (0.0231 ± 0.0021)
2.958 ± 0.296 (0.179 ± 0.035)	66.1 ± 26.2 (0.058 ± 0.0055)	43.5 ± 23.7 (0.0699 ± 0.0064)
3.5 ± 0.25 (0.25 ± 0.035)	118.5 ± 30.3 (0.125 ± 0.012)	98.4 ± 30.3 (0.15 ± 0.014)

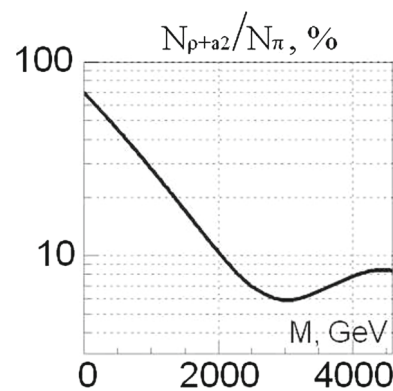


Fig. 5 Corrections (in percents) to extracted cross sections related to additional ρ and a_2 induced background processes in the single charge exchange versus the energy of the πp interaction (M)

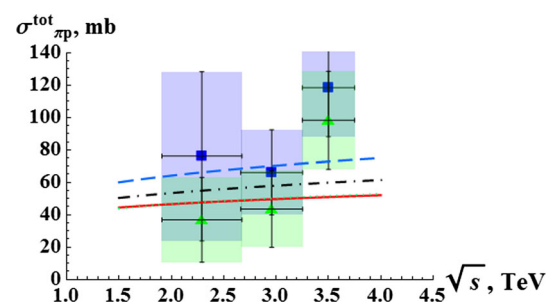


Fig. 6 Extracted total $\pi^+ p$ cross sections presented in the Table 1 versus different parametrizations: [35] (solid), [36] (dashed), [37] (dotted) and [38,39] (dash-dotted). Two intervals of t related to η regions of the LHCf are $8.81 < \eta < 8.99$ (triangles) and $8.99 < \eta < 9.22$ (boxes)

but we can see the tendency in Fig. 6. Our assumption was that this t dependence is rather weak. The data confirms it rather well.

4 Conclusions

This paper was inspired by the latest LHCf data [20] on the SCE process at 7 TeV. The analysis of these data is the first attempt to extract pion–proton total cross section at TeV energies. The observation of SCE confirms that our expectations [1–4] were realistic.

With the data on p p total and elastic cross sections at 7 TeV and higher [26] theoretical errors of absorptive corrections have been reduced significantly, since parameters of the model for these corrections are obtained by fitting the total and elastic cross sections. There is some disagreement with other authors [28, 29], who propose a stronger suppression factor. They considered scattering of higher Fock components of the projectile proton, which contain a color octet dipole. In this case absorption occurs due to pomeron exchanges between these components and the initial (final) hadron, as depicted in Fig. 5c of Ref. [23]. Since they have no calculations for single pion exchange at LHC, we can estimate their result from calculations for double pion exchange in [29]. They use the flux factor, which is equal to our function \tilde{S} with $|t_{\min}| \simeq m_p^2 \xi^2 / (1 - \xi)$ and $|t_{\max}| = \infty$ in (5). In their case \tilde{S} is approximately 15% smaller than our result. So we can suppose that the extracted values of the pion–proton cross sections will be about 15% higher than in Table 1.

Since calculation of absorptive corrections is the critical point, we will discuss this question in detail further, especially in processes like $\gamma^* p \rightarrow X n$ or $\gamma^* p \rightarrow \rho \pi n$, where we have experimental data.

Unfortunately, experimental errors of the LHCf are huge. Nevertheless, we can try our method to extract the pion–proton total cross section in the TeV energy region and make preliminary conclusions on its behavior at different values of t .

If measurements are done more accurately then we will have additional and richer data in the high energy region to check predictions of different models for strong interactions, quark counting rules, “asymptopia” hypothesis, and so on.

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